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Hydrography of Scottish Coastal Waters

By R. E. CRAIG, B.Sc.

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1958 No. 2

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By R. E. CRAIG, B.Sc.

Marine Laboratory, Aberdeen

EDINBURGH: HER MAJESTY'S STATIONERY OFFICE

1959

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Hydrography of Scottish Coastal Waters

INTRODUCTION

This paper describes the evidence and impressions gained from several years' observations. It is hoped that the form of presentation will be convenient for reference and will provide a suitable basis for future investigations.

The first section describes the "usual" distribution of temperature and salinity using hydrographic charts with a minimum of written description, and illustrates by a few particular examples the degree of variability which can occur.

The second section proposes a "usual" system of water movement that is consistent with the observed salinities, and there is discussion of the limited direct evidence about these water movements.

The third section describes conditions in Scottish estuaries.

SECTION I.

SALINITY AND TEMPERATURE DISTRIBUTIONS

Salinity Distributions (*See Figs. 1 and 2.*)

These distributions have been arrived at by taking as a basis the monthly mean charts prepared for the International Council for the Exploration of the Sea by Commander J. R. Lumby. Detail has been added for the Scottish Coastal Area from the large number of surveys by Scottish Home Department vessels. Some of these detailed surveys have already been published (Craig, 1952-1958). In the charts salinity has been presented as D.C.I. or "defined coastal influence," which is equal to $1 + \log_{10} (35{\cdot}5–S)$ where S is the salinity in parts per thousand (Craig, 1954); a conversion table to salinity is given in Appendix I. In regions where the variations in salinity are mainly due to dilution by fresh water from the land, as in most of those covered by this paper, the use of D.C.I., being approximately proportional to the logarithm of the degree of dilution, has certain advantages. Thus deviations by more than 0·1 from the values given in the charts in this paper would equally be worthy of note, whether occurring in estuaries or in the open sea. For biological purposes a careful study of Appendix I is recommended. It will be observed that the subdivisions of D.C.I. split a wide range of salinity into useful zones of interest. Two charts are presented showing D.C.I. at surface and bottom in winter. Seasonal changes are covered by the following remarks:

(*a*) In inshore regions salinities are slightly higher (D.C.I. somewhat lower) in summer due to generally lower river flow. The effect is small compared with day-to-day variations.

(*b*) In offshore parts of the region salinities at the surface tend to decline in summer, the outward spread of diluted water being then less inhibited by vertical mixing. This effect is small compared with daily and seasonal variations except as noted in (*c*).

(*c*) The region west of the Shetlands, Orkneys and Hebrides shows a highly significant seasonal change. Here, in summer, coastal water overlies oceanic water and extends westward beyond the edge of the shelf. It also extends northwards to 60° 30′N. in a broad tongue to the west of Shetland. In winter the extension of coastal water is much less—to about 59° 30′N. only—and vertical stratification almost disappears.

This seasonal change is well shown by hydrographic sections on the Butt of Lewis-Faroe Bank and Nolso-Flugga lines (Tait, 1957).

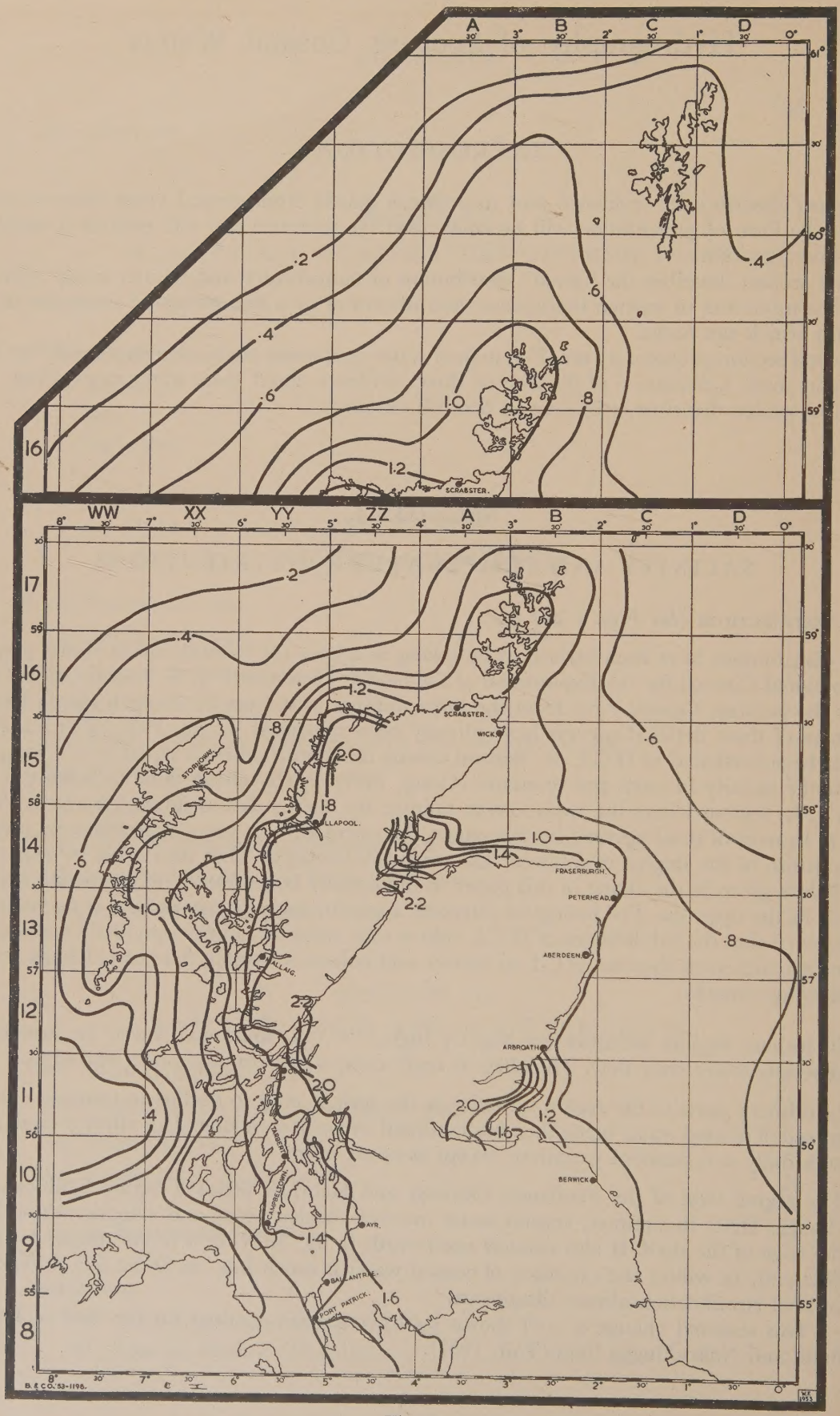
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Fig. 1

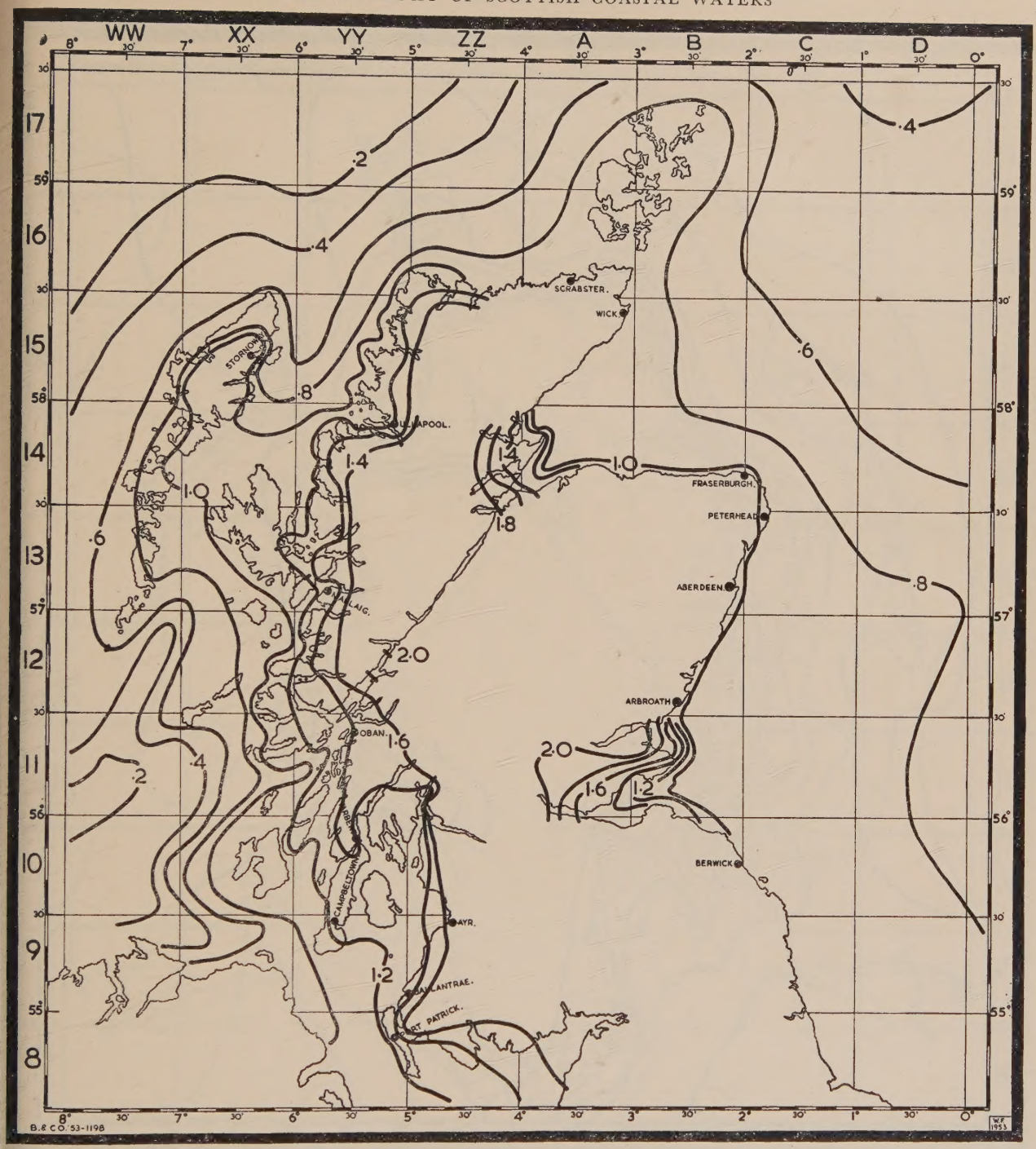

Fig. 2 Typical values of the salinity of the bottom water (expressed as D.C.I.). Seasonal changes are negligible.

Fig. 1 Typical values of the salinity of the surface water in winter (expressed as D.C.I.). No significance attaches to isohalines crossing the land, except that by drawing them thus the figure is simplified. It will be appreciated that the presentation of fine detail is impossible on a reasonable scale of chart and every inflowing stream will raise the D.C.I. in the immediate vicinity of its mouth.

During the summer period May to October the extension of coastal water west of the Outer Hebrides becomes somewhat greater (by 10 to 20 miles) and there is considerable spread northwards of coastal water between longitudes 3°30′W. and 5°W. to the extent of about 40 to 50 miles. (See small upper chart.)

Fig. 3 Typical values of surface temperature in February. Over most of the area the bottom temperature is similar, but the oblique figures indicate the quantity *in tenth degrees* which should be *added* in particular regions to obtain the bottom temperature.

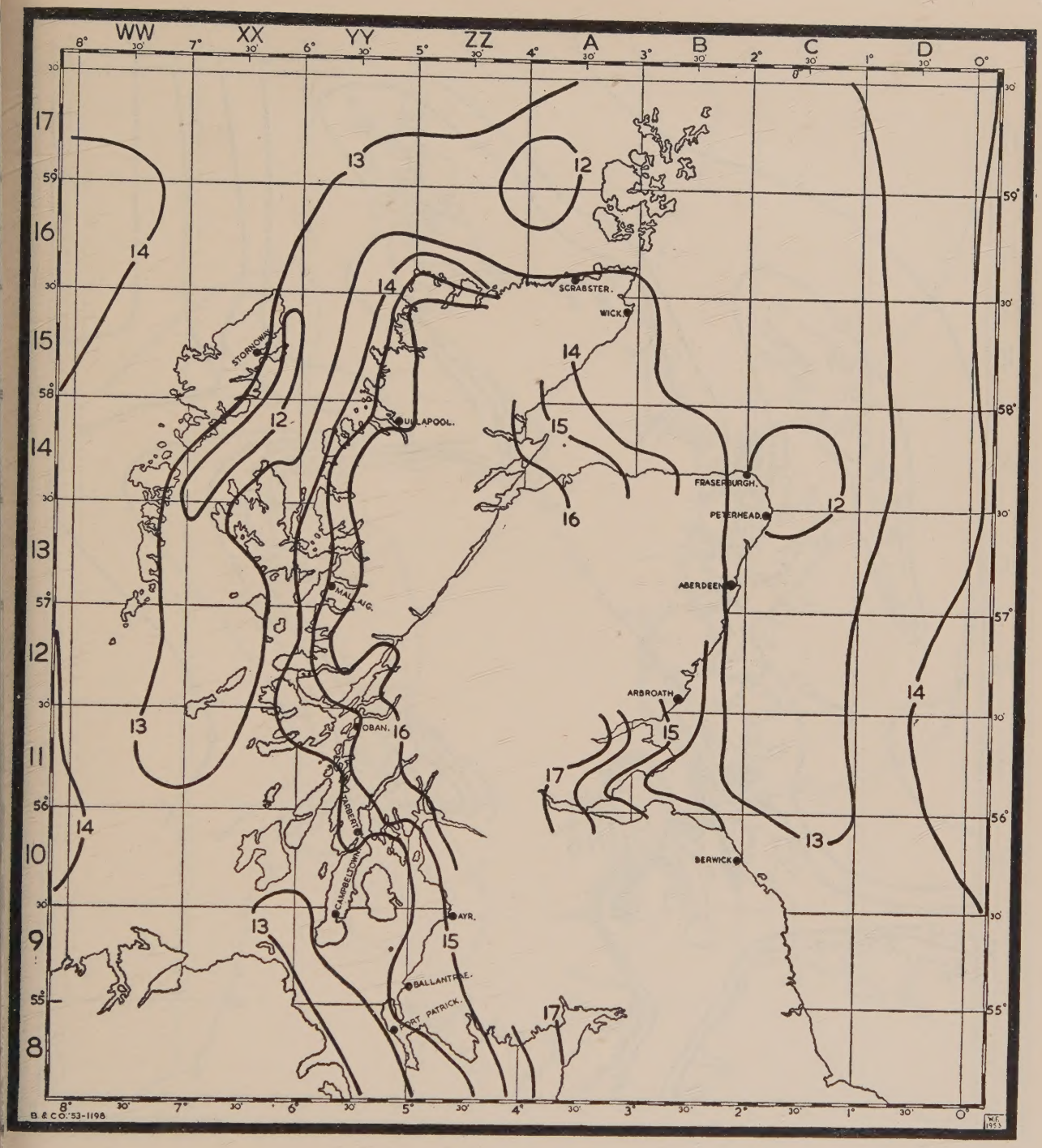

Fig. 4 Typical values of surface temperature in mid-July. At about this time the main east coast temperature gradient changes from warmer in the north to warmer in the south.

Fig. 5 Typical values of bottom temperature in mid-July. In certain west coast regions, isolated pockets of bottom water remain below 8°. These are indicated in black. It is naturally impossible to show the intermediate isotherms which closely surround these pockets.

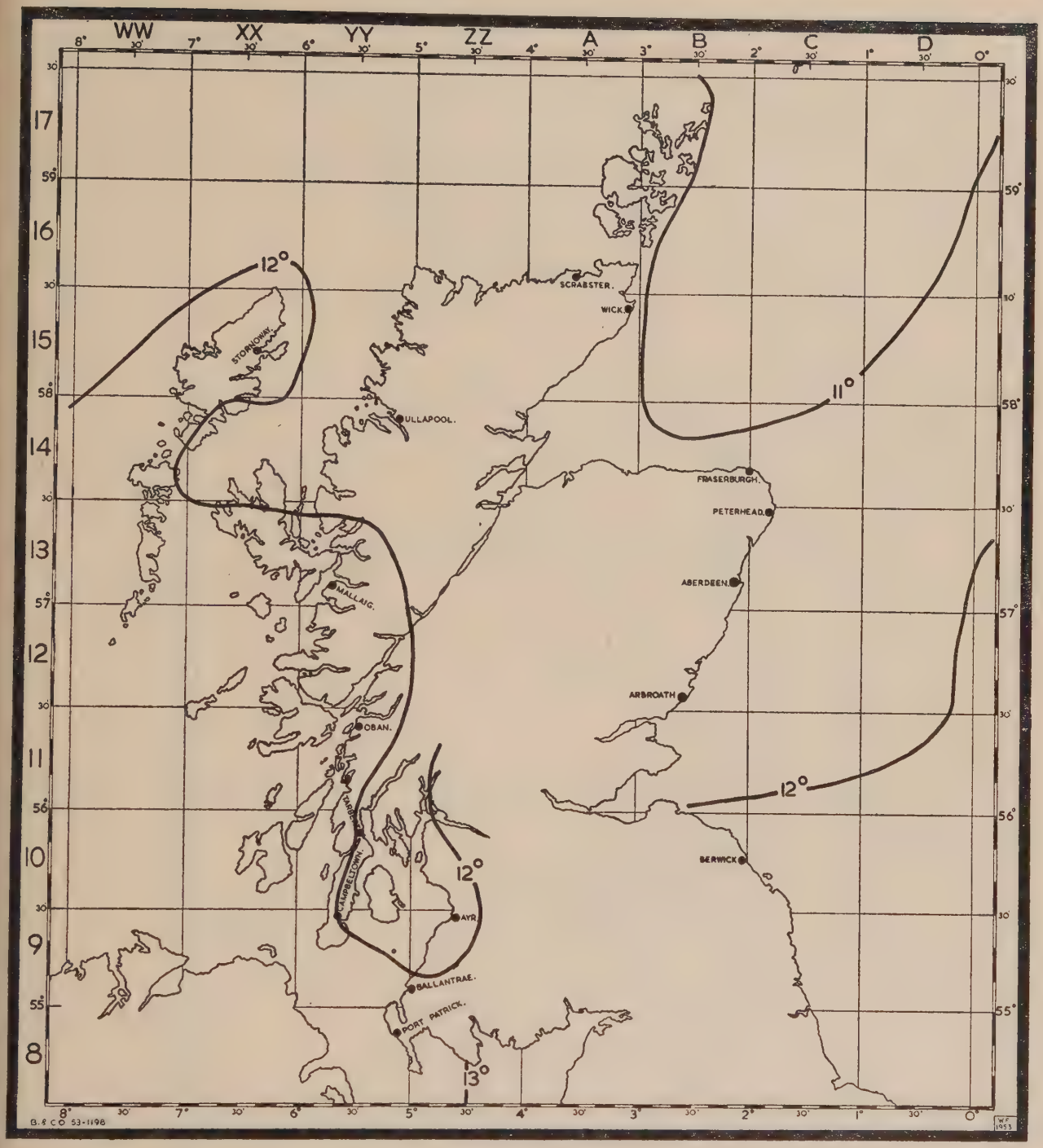

Fig. 6 Typical values of surface temperature at about 1st October.

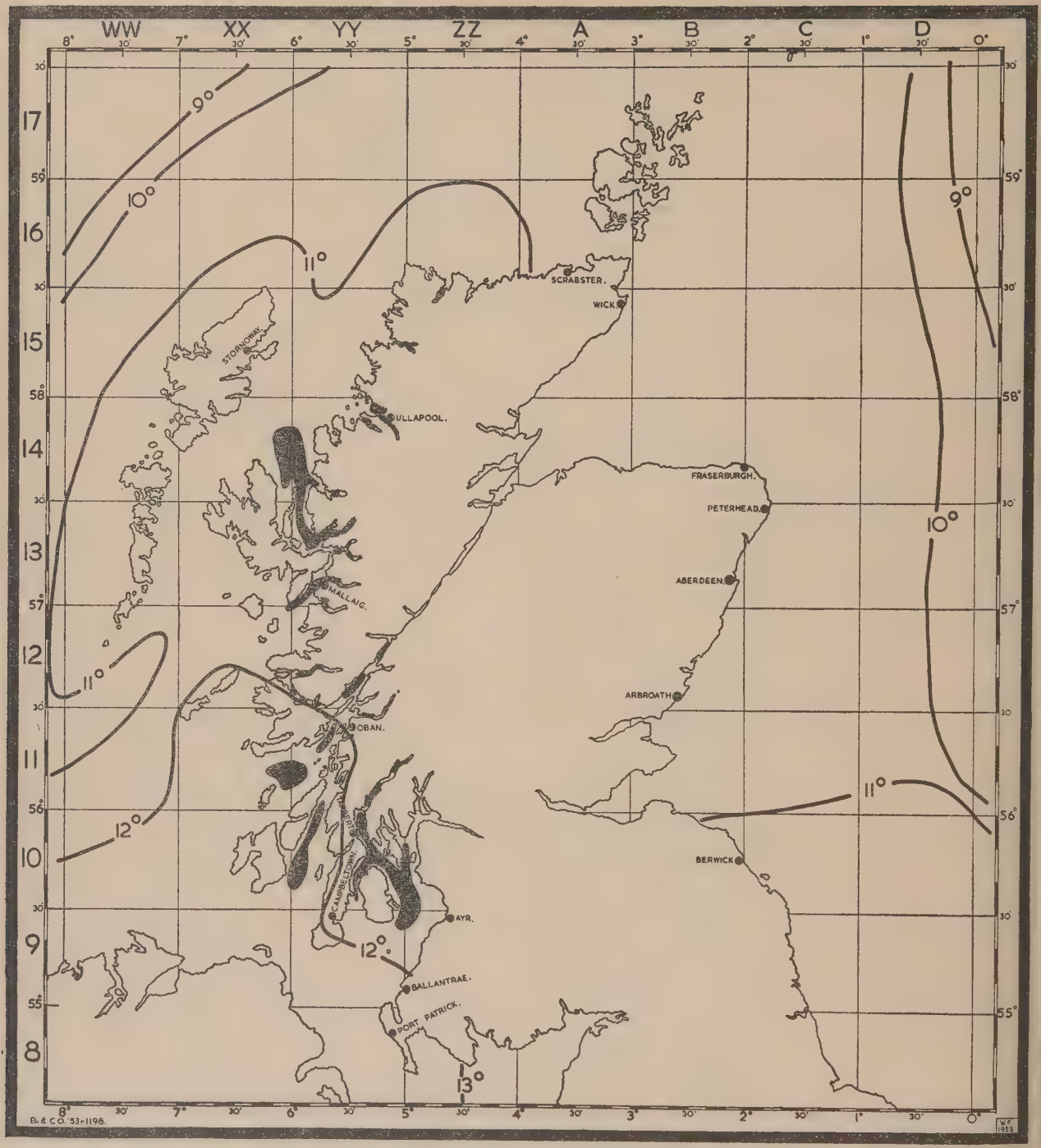

Fig. 7 Typical values of bottom temperature at about 1st October. The isolated pockets of cold water lose their identity during October or early November.

Temperature Distribution (*See Figs. 3, 4, 5, 6 and 7.*)

February (*Fig. 3*).

In late February temperatures are at a minimum and the water column is vertically homogeneous except where there is dilution of the surface water. Thus in inshore regions, typically, the surface water may be $\frac{1}{4}°$ to $\frac{1}{2}°$C. cooler than at the bottom. In certain regions of cold streams this differential may reach 1° to 2°C. Such streams occur in the north-eastern Minch, and along the south shores of the Moray Firth and the Firth of Forth. In some estuarine regions and at river mouths where tidal mixing is slight, as at the Aberdeenshire Dee, the surface water may be as much as 4°C. cooler than the bottom water. It has been thought best to show the surface temperature with some indication of the usual differentials.

Horizontal changes at this season are regular and smooth except close to river mouths, where patches of cold dilute water may be encountered.

July (*Figs. 4 and 5*)

During the period April-June surface temperatures in the offshore region rise steadily through about 7°C., but in some years by at least 9°. In inshore and estuarine regions the rise is greater, amounting to about 15° at such places as Kincardine-on-Forth. The rate of rise of surface temperature depends naturally on the depth of water and the degree of vertical mixing by both wind and tide. Thus year to year differences will depend mainly on the incidence of wind, and local differences principally on depth and tidal mixing.

For example, the region to about 30 miles east of Rattray Head in depths up to 80 metres shows a

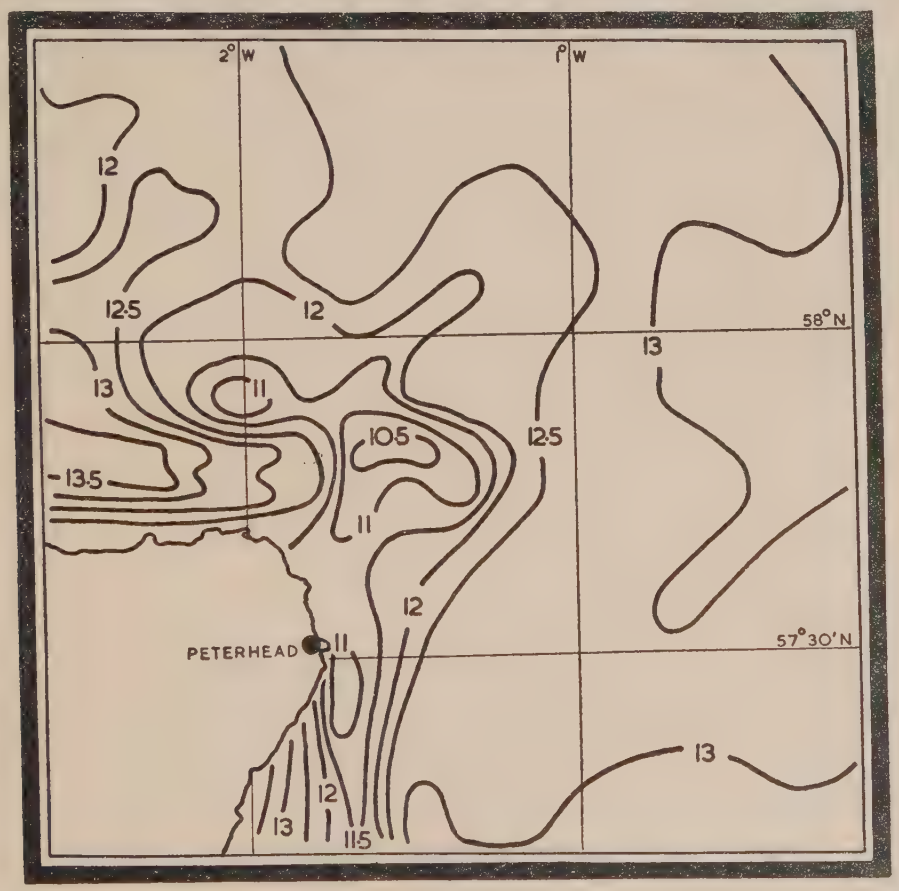

Fig. 8 An example of surface temperature distribution in the Buchan region (7th-11th July, 1952), based on about 100 observations, and showing the complex pattern and large horizontal gradients of temperature which are not unusual in the period June-July in this region.

relatively slow rate of rise, since tidal mixing is strong and the depth enough to absorb a good deal of heat. Similarly the Fair Isle region shows a very slow rate of rise.

As a result of these processes steep horizontal temperature gradients develop and subsequent water movements and mixing may mask the original local causes. An example of an extreme case is shown in Fig. 8. Patchiness due to irregular mixing may occur also to a degree that precludes charting of the temperature distribution altogether. Such patchiness can be very marked in the north-western Minch and in the region west of Orkney. An example of a surface thermograph record of this type is given in Fig. 9.

At depths greater than 100 to 110 metres the temperatures do not rise greatly during this period, except where there is invasion by an oceanic water mass. This occurs principally to the east of the Shetland and Orkney Islands.

September (*Figs. 6 and 7*)

The upper water continues to gain heat from the sun until the end of August at least, but before that time the removal of heat by downward mixing overtakes this gain and surface temperatures generally decline during August. In water of less than 40 metres depths, however, surface temperature may not decrease until September. The mixing process is essentially rather patchy so that for a time the distribution of bottom temperature shows regions at about 10°C. intermingled with areas remaining at their August values of $7\frac{1}{2}°$ to 8°. These remarks refer to the important zone with depths from 60 to 120 metres off the east coast of Scotland.

This breakdown of stratification occurs first over the moderately shallow and extensive Turbot Bank, but the deeper regions around the bank reach the same condition within a period of two or three weeks, and in any case by the end of September. This should be contrasted with conditions further offshore on the Fladen ground in depths greater than 140 metres. Here mixing is not usually complete until late November or December.

Thus by the end of September Scottish coastal waters to a depth of 120 metres have a relatively simple temperature distribution. Vertical change of temperature is negligible everywhere. Off the Aberdeenshire coast and north to East Shetland temperatures are about 10° to 11°C. To the south temperatures rise to about 12° off St. Abb's Head, and from west Orkney southwards to the Clyde there is a similar slow rise to 12° or 13°.

From this time forward the large horizontal gradients characteristic of summer are absent. Temperatures decline steadily to the February minimum, and from late October the estuarine and diluted surface water can again be distinguished by its relatively low temperature.

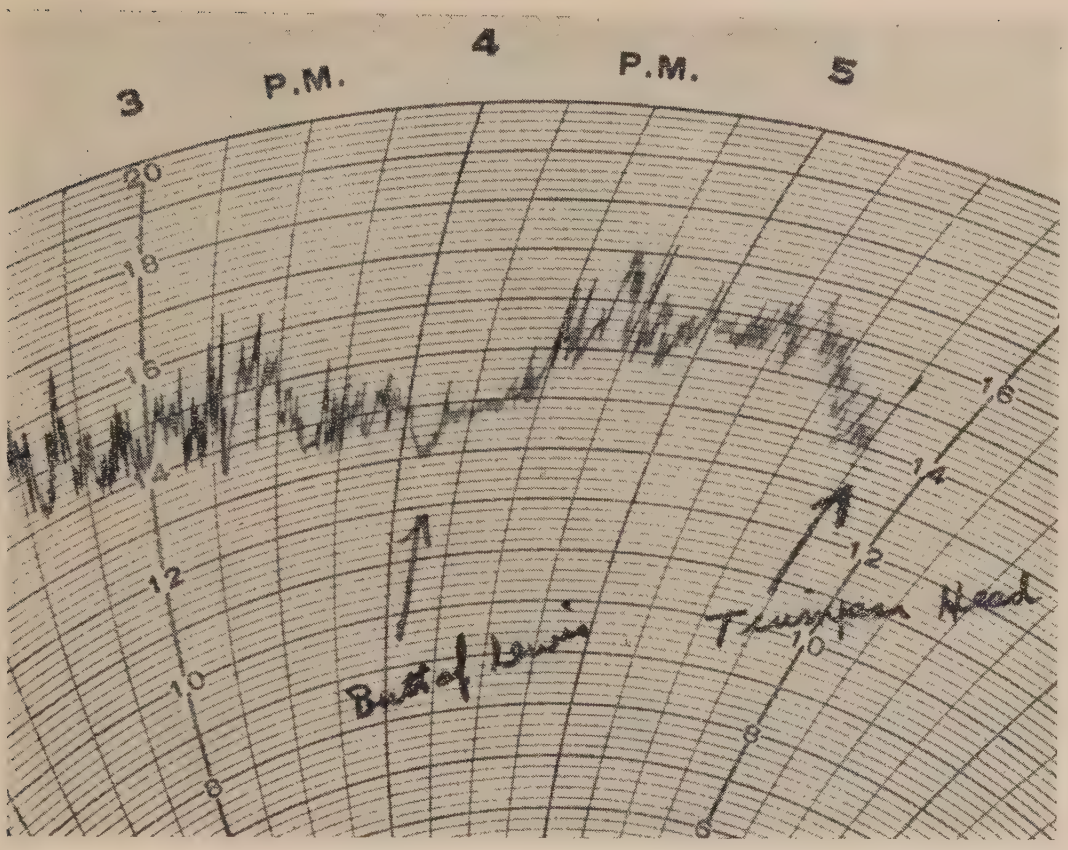

Fig. 9 Surface temperature recorded by the thermograph of a research vessel approaching the Butt of Lewis from the north-west and proceeding south to Tiumpan Head (10th July, 1955). The distance covered by this record is approximately 25 miles, and it is a rather extreme example of patchiness due to the breakdown by tidal mixing of an unusually warm surface layer. This had resulted from a very hot, sunny spell of weather.

SECTION II.

WATER MOVEMENTS

Water movements in the Scottish coastal region are variable and neither the mean motion, nor the extremes may be stated with accuracy. Some idea of the mean motion may be obtained by tracing the dispersal of land drainage water, and this has been done taking account of the general pattern propounded by Tait (1937) for the surface water drift, and such new direct evidence as exists from drift-bottle and drift-indicator returns.

Estimates of land drainage water are obtained from the Meteorological Atlas (Meteorological Office, 1952), being calculated from the mean annual rainfall over the catchment area concerned, diminished by the mean annual evaporation loss, which is taken to be fifteen inches (c.f. Mill, 1891). Rainfall on and evaporation from the sea surface have been neglected since their effect is small compared with the influence of land drainage.[1]

The North Channel

The cross section area of this channel between the Mull of Kintyre and Ireland is about 1·5 square kilometres. The volume of the Irish Sea is about 5,000 cubic kilometres, and according to Bowden this water is replaced in about three years. If the whole channel were occupied by this north-going water, a mean velocity of about three kilometres per day would be enough to accomplish this exchange. However, the available data (Craig, 1956, 1957) suggest a south-going stream of coastal water from the north of Ireland in the deep region on the Irish side of the channel. This water is detectable on occasion as far south as a line from Strangford Lough to the Mull of Galloway. From the dynamic situation in the available sections, it seems reasonable to suggest a typical velocity for the north-going stream of about five kilometres per day, while the south-going stream probably does not exceed a velocity of one kilometre per day.

The north-going stream occupies about two-thirds of the cross section area of the section and its volume transport is therefore about five cubic kilometres per day, of which about half a cubic kilometre is water drawn from the north of Ireland. Figs. 10 and 11 may be consulted in this connection. They are relevant to the whole of this section.

The Firth of Clyde

This is not a typical estuary, and is in some ways more comparable to a deep loch. A great part of the Firth exceeds 150 metres in depth, and there is a sill lying between Ballantrae and the Mull of Kintyre with a depth of only 40 metres. The salinity of the water of the Firth normally lies below 34‰ (D.C.I. normally in excess of 1·2).

The annual run-off of fresh water is about three cubic kilometres, and the difference in salinity between the in- and out-flowing water is about 0·5‰. This suggests an annual intake from the North Channel of about 150 cubic kilometres, and since the volume of the Firth is about 100 cubic kilometres (Mill, 1891) we conclude that replacement of the water of the Firth takes about nine months. The water in the deep basin remains in summer at temperatures below 9°C., and oxygen values drop to 3 ml/litre or less. It seems clear that effective exchange of this deep water can occur only during the winter months.

It follows that only a part of the Irish Sea outflow water can enter the Firth of Clyde. In fact the estimated inflow of 150 cubic kilometres per year, or one-third cubic kilometre per day, is about one-fifteenth of the north-going water in the North Channel.

Drift-indicator and drift-bottle experiments suggest an *internal* circulation in the Firth of Clyde, and in fact a hydrographic section from the south of Arran to the Irish coast suggests a "double wedge".

[1] In Scottish latitudes, over the whole year, precipitation over the sea exceeds evaporation. That the net effect is not great is evidenced by the slowness of the change of surface salinity in the main Atlantic stream in the direction of its motion. A detailed study of the matter is given by Bowden (1955) in the case of the Irish Sea. Difficulties arise, and approximate corrections have been made by estimations in the case of certain sea lochs which share in the high orographic rainfall of neighbouring districts.

Fig. 10 Estimated most usual net water movements at the surface. The figures indicate approximate drift speeds in *kilometres per day*.

Fig. 11 Estimated most usual net water movements near the bottom. The figures indicate very approximate drift speeds in *kilometres per day*. It will be appreciated that the sum total of evidence for this figure is much less than in the case of Fig. 10, and accordingly it should be accepted as a preliminary estimate only.

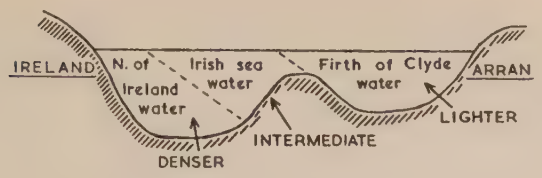

Fig. 12 Distribution of water masses in a section from the south of Arran to the Irish coast. Diagrammatic only, to illustrate the discussion in the text.

This is shown in Fig. 12. The Clyde water in the sill region has a north-westerly motion relative to the Irish Sea water. Near the Ayrshire coast and near the Mull of Kintyre the boundary between Firth of Clyde and Irish Sea water is much less sharp than in mid-Firth, and the general impression is of water exchange taking place between two streams moving in approximately parallel courses. A clockwise circulation round Arran appears to be the most usual regime within the Firth, as is suggested by Fig. 10.

The Region from Ireland to Skye

Water of near-oceanic salinity occupies a region from Barra Head to 56°N. forming a tongue directed inward towards the South Minch and the Firth of Lorne (Craig, 1956, 1957). There is a well defined coastal stream of diluted water, and it is noticeable that whereas there are relatively homogeneous conditions in the North Channel, the extra run-off from the land builds up a characteristic wedge further north. This remains distinctive as far as the Central Minch, where strong tidal action again produces an unusually homogeneous mass within which, in a region about fifteen miles square, there is typically no detectable variation in temperature or salinity.

It will be convenient to summarize here the land drainage to be accounted for and removed by the west coast circulation. This is as follows:

Irish Sea	35	cubic	kilometres	/year
West and North Ireland	40	,,	,,	,,
Firth of Clyde	3	,,	,,	,,
Scotland (Mull of Kintyre to Skye)	18	,,	,,	,,
Outer Hebrides	1	,,	,,	,,
Scotland (Skye to Cape Wrath)	9	,,	,,	,,
Scotland (North Coast)	3	,,	,,	,,

It follows from these that the coastal stream when it reaches the South Minch must carry 96 cubic kilometres/year of fresh water. The salinity of the Central Minch is about 34·5‰, i.e. it contains about 3% of fresh water. The cross section area of the channel is about 1·8 square kilometres, and thus a flow of about 5 kilometres/day would suffice to transport all the fresh water. However, it is unlikely that the flow is as great as this. The South Minch, and the region immediately to the south of it, is an area where mixing takes place between coastal and oceanic water. Some of this mixed water spreads to the westward round Barra Head and so the general northward flow is divided by the island chain of the Outer Hebrides. There is no direct evidence concerning the fractions into which the stream is divided and, pending a more exact determination, it is assumed that flow through the Central Minch accounts for about two-fifths of the total, giving a velocity there of about 2 kilometres/day. The remaining three-fifths of the fresh water passes to the west of the islands and typically occupies the region to about half way out on the shelf. It extends to about 15 miles north-west of the Butt of Lewis and the dilution extends to about 150 metres depth.

To return, however, to the area which is the subject of this subsection, it may be noted that the greatest dilution occurs where run-off is great and the escape path restricted. Excluding the sea lochs, two regions may be noted as more diluted than the rest. These are (i) the Firth of Lorne, and (ii) the regions between Skye and the mainland—to be precise, the Sound of Sleat and Inner Sound.

Skye to Cape Wrath

The North Minch contains three water masses. The largest of these is derived from the Central Minch Close to the eastern shore is a more diluted stream formed by fresh water from the mainland mixing wit Central Minch water. This occupies the upper layers from Inner Sound to Cape Wrath. The third, an most saline, component enters from the north-west. It is derived from the coastal stream west of th Hebrides, whose origin was discussed in the previous section. This inflow to the North Minch seems to b analogous to the North Channel counter current into the Irish Sea. The southern limit of its extent i the latitude of Kebock Head; on occasions its influence reaches no further south than Chicken Hea (Craig, 1952).

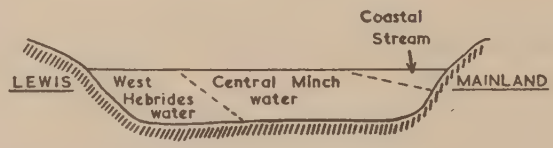

Fig. 13 Distribution of water masses in the North Minch in a section from Handa Island to Tiumpan Head. Diagrammatic only, to illustrate the discussion in the text.

Thus there is a double wedge system in a section eastwards from Tiumpan Head, as suggested by Fig 13, though the boundaries are not at all sharp. Typical salinities are: West Hebrides Water—34·7‰ Central Minch Water—34·5‰, Coastal Stream—34·0‰. The coastal stream of newly diluted wate occupies about $\frac{1}{2}$ square kilometre in the section, probably rather less. Since it has to remove 9 cubi kilometres per year of fresh water, we arrive at an estimate of its northward movement as about kilometres per day, and this incidentally removes also 2 cubic kilometres per day of the main body c Central Minch water.

This main body has been assessed rather arbitrarily as carrying about 4 cubic kilometres per day c Central Minch water, and also water derived from the counter current. The area of the whole sectio is about 6 square kilometres, of which about two are occupied by the counter current and three and half by the Central Minch water (the remaining half square kilometre is of course the coastal stream There seems no good reason to think the rate of flow of the main body is greater than 1 to $1\frac{1}{2}$ kilometr per day. If the former figure is taken, it gives a transport of $3\frac{1}{2}$ cubic kilometres per day, of which 1 cubic kilometres per day must be supplied by the counter current. This gives a rate of southerly flo for the counter current, in the Tiumpan Head region, of rather less than 1 kilometre per day, which i not much different from the rate deduced for the North Channel counter current.

It seems reasonable to think that a typical value for the counter current is between $\frac{3}{4}$ and $\frac{1}{2}$ kilometr per day and that the northward movement of the main body is at a rate of 1 to $1\frac{1}{2}$ kilometres per day For these two water masses, the surface and deep values of velocity are likely to be similar, as each i fairly homogeneous vertically.

The North Coast of Scotland with the Orkney Islands

In this region the land drainage per mile of coast is much less than on the west. The stream of ve dilute water from the Eastern Minch swings to the eastward as might be expected. The new dilutio however, is not enough to counteract mixing and the stream loses its identity before reaching th Pentland Firth. The evidence of salinity patterns and drift bottles (Tait, 1937) is that the net flow throug the Pentland Firth is towards the west. Thus it will not usually be a point of entry to the North Sea fo plankton.

Since the narrow coastal stream ceases to be distinctive, the main feature of the region is a broa stream of mixed coastal and oceanic water moving from the Minch towards the Orkney-Fair Isle passage The stream consists of water of salinity about 35·3‰ (D.C.I. = 0·3) at its outer limit and 34·7 to 34·1 on its inner edge (D.C.I. = 0·9 to 0·8), the salinity at the outer limit being determined by the state c the oceanic stream.

As already mentioned, the limit of this stream in winter is a smooth arc from just west of the Butt of Lewis to Fair Isle, but in summer it loops far to the north, sometimes to the latitude of Flugga and then southward to Fair Isle. The mean breadth of the stream is about 30 miles, and of course there may be eddy motion within it. However the net transport of fresh water must be the sum of the drainage of all the regions considered, or at any rate will not on the average exceed this total of 109 cubic kilometres per annum.

A content of 1% fresh water is estimated from the salinity, and so a transport of 10,700 cubic kilometres per year of diluted water seems a reasonable assessment, i.e. about 30 cubic kilometres per day. Since the cross section area of the stream is about 5 square kilometres, the rate of movement to the north-east must be about 6 kilometres per day. The average surface movement will be rather more rapid and the average deep movement rather less, since much of the area is subject to vertical layering in the summer. In winter and early spring however, the region is vertically homogeneous, and the surface and deep velocities are probably similar. It has been pointed out (Craig, 1954) that small patches of relatively high or low salinity in the spring tend to occur at both surface and bottom in the same locations. Since it is not easy to visualize heavy dilution occurring offshore in a patchy way this tends to confirm the similarity of surface and deep movements at this time of the year.

To the north-west of the coastal water lies the oceanic stream of the Faroe-Shetland Channel within which velocities of the upper water may reach values in excess of those shown in Figs 10 and 11 (Tait, 1957).

The Region East of the Orkneys

The stream of mixed water from the Orkney-Fair Isle Channel swings to the south into and across the Moray Firth. Its seaward limit (very roughly at 1°W. longitude) joins the relatively unmixed oceanic water stemming from the north of Shetland. The cross section area of the stream is just about the same as in the Minch-Fair Isle region and the rate of flow will therefore be similar.

The Moray Firth

Before considering details we shall here set out estimates of land drainage, as has been done for the west and north coasts:

Moray Firth	18	cubic kilometres/year		
East Coast (Fraserburgh-Arbroath)	3	„	„	„
Rivers Tay and Eden	12	„	„	„
Firth of Forth (Fifeness-St. Abb's Head)	3	„	„	„
Total East Coast	36	„	„	„

For comparison the figure of 109 cubic kilometres per year for all sources west of Orkney should be recalled. It is very clear that the most important sources for the dilution of the north-western North Sea are to the west of Orkney.

The Moray Firth with depths in the region of 40 to 60 metres is shallow compared with the sea to the eastward. Close to the southern shore, however, there is an irregular deep trench with depths as great as 250 metres. The circulation in the Firth is of the typical estuarine form. The greater part of the diluted water, resulting from local run-off, flows out as a wedge in the upper layers close to the south shore. In August-September this stream is generally a little warmer than its surroundings. In winter and spring it forms a distinctive cold stream.

The outflow salinity in the Kinnaird Head region is about 34·3‰ while the inflowing water has a salinity of about 34·9‰, so the outflow contains about 2% of local diluting water. Thus the rate of change of Moray Firth water must be of the order of $50 \times 18 = 900$ cubic kilometres per year, or about 3 cubic kilometres per day. This suggests that the water of the Firth will be replaced in about three or four months, since the volume of the Firth is of the order of 250 cubic kilometres.

The distribution of bottom salinity suggests that the main inflow is a deep one occurring under and immediately north of the outflow stream, in the deepest part of the Firth. The northern region, including Smith Bank, is therefore an area in which in- or outflow is relatively slight. Tait (1937) has deduced from drift-bottle returns that a clockwise eddy is a common feature of this region.

The cross section area of the outflow current is about 0·3 square kilometres and the transport is about $2\frac{1}{2}$ cubic kilometres per day. This gives an estimate of 8 kilometres per day for the flow along the south shore. The maximum rate at the surface is probably greater—about 10 to 12 kilometres per day, while the deeper portion of this stream will move at less than 8 kilometres per day.

The inflowing water has a much larger cross section area which is difficult to assess accurately since this water is not dissimilar to that on the southern margin of the eddy. An approximation would be 1·3 square kilometres, giving a rate of flow of about 2 kilometres per day.

The eddy must derive its motion from the inflowing stream and from the main S.S.E. flow past the mouth of the Firth. The main stream has a velocity, similar to that off East Orkney, of about 6 kilometres per day, and so the velocity of the Moray Firth eddy at its perimeter probably lies between 2 and 6 kilometres per day. If we take the value to be 4 this gives the eddy a period of rotation of about seven weeks.

Within the Moray Firth a sharp thermocline has been observed only in the deep southern region where the depth exceeds 120 metres. Conditions in the uppermost part of the Firth and in the small adjoining firths are truly estuarine and are dealt with later.

The Coastal Region from Fraserburgh to Arbroath

Vigorous tidal mixing occurs in a large region extending about 15 to 20 miles eastward of Rattray Head and Buchan Ness. The various streams converging on this area thus lose their identity quickly. In summer, also, when a thermocline is set up in the centre of the northern North Sea, its inshore limit remains about fifty miles from the coast in this region. Further south, off Arbroath, on the other hand an abrupt thermocline may be found as close as 30 miles from the coast. Assessment of the usual water movement in the coastal region is difficult. Tait (1937) deduces from drift-bottle returns that an eddy (the East Scottish Coast eddy) is typically present. The writer, using drift-indicators recovered at sea by fishing vessels (Craig, 1957), has consistently found movements in a direction between south and east. On occasions, however, dilution apparently due to the Dee and Don which flow into Aberdeen Bay, has been detected to the north and east of Aberdeen, as well as to the south.

It is not impossible that the disagreement between drift-bottles and drift-indicators is due to differences in conditions between the years studied, and it may be best to say that while the drift 50 miles or so offshore is generally conditioned by the main North Sea inflow and is to the south or south-east, the flow inshore is more variable and subject to reversal or the occasional establishment of eddy motion.

This east coast region provides some additional diluting water (about 3 cubic kilometres per year) to the main North Sea circulation. The total annual transport of fresh water by the circulation has thus reached 109 + 18 + 3, i.e. 130 cubic kilometres in the latitude of Arbroath, or would have done if none of this water had found its way across to the eastern side of the North Sea. However, it may be accepted that water of predominantly Atlantic character is exceedingly rare south of 58°N. latitude, so it is probable that significant loss of coastal water by eastward mixing does occur. Thus the method of tracing the land drainage water cannot be applied to the main stream further south than Aberdeen.

St. Andrews Bay and the Firth of Forth

The Tay estuary and the upper Forth are considered in a later section. Here we may note that there is a large annual contribution of fresh water into St. Andrews Bay, about 12 cubic kilometres in fact, of which almost the whole comes from the Tay. The turbid water from the Tay estuary, on a calm day, extends four or five miles to seaward as a well defined stream. Its southern edge can on occasions be defined within about one metre, so clear cut is the transition when the ebb tide is running. Eventually, however, tidal mixing spreads this water in a general east and south direction. In the southern part of St. Andrews

Bay salinities of 32-34‰ prevail. A part of this Bay water is carried into the Firth of Forth, and is detectable in the region between the Isle of May and Crail, and as far west as Pittenweem (Mill, 1885; Craig, 1952).

Only a portion of this Tay outflow finds its way into this distinctive patch. The greater part is spread into the main coastal stream, so that the main inflow to the Firth of Forth consists of water already well diluted, with a salinity of about 34·5‰. The Firth itself is a good example of the estuarine type of circulation. Most of the fresh water enters via the upper Firth, from the Rivers Forth, Teith, Devon and Carron. Further to seaward there is more dilution from the south shore than from the north, the Rivers Almond, Water of Leith, and Esk being quite significant, and the East Lothian Tyne is also important. On the north side, the Leven is the only river of any importance.

Unlike the Moray Firth, there is no indication of any important fixed eddy. The outflow stream has a salinity of 32 to 34‰ in the North Berwick region and lies in a characteristic wedge along the south shore. It therefore carries about 5% of local diluting water and carries about $2\frac{1}{2}$ cubic kilometres per year of locally derived fresh water. Thus in total about 50 cubic kilometres must pass seaward annually through a cross section area of about 0·1 square kilometres. Its velocity is therefore about $1\frac{1}{2}$ kilometres per day. The inflowing water is spread over a larger cross section, and its velocity is estimated to be of the order of $\frac{1}{2}$ kilometre per day.

Since the volume of the Firth is about 30 cubic kilometres it is clear that the time for complete exchange of the water is about three-fifths of a year or roughly eight months. Proceeding up the Firth, the mass transport of the in- and outflowing streams becomes progressively less, and so also do the dimensions of the Firth. The velocities in fact increase, so that in the Oxcars region inflow is at a rate of about $1\frac{1}{2}$ kilometres per day and outflow perhaps 3 to 4 kilometres per day. Further up still the velocities increase greatly, as will be seen in a later section, a mean rate of inflow and outflow of about half a knot being reached in the Bo'ness section and maintained for some miles up into the river section.

The outflow stream from the Firth can be clearly distinguished as far seaward as St. Abbs Head, but seems here to lose its identity by mixing with the general mass of coastal water. The contribution of fresh water from the East Lothian Tyne is generally enough to be detectable on salinity charts, thus the water off Dunbar may have a salinity as low as 32‰ on occasions.

Due to the fact that the inflowing water tends to keep to the north, and to the small rate of dilution on this side, the northern part of the Firth is relatively marine and generally homogeneous vertically. Thus, for instance, Largo Bay is in marked contrast to its neighbours, St. Andrews Bay and Aberlady Bay, in both of which marked salinity gradients are usual. In spite of its generally low salinity of about 33·8‰, Largo Bay must be regarded as a region bathed in inflowing water. Probably a great part of the dilution there is derived from St. Andrews Bay, and it has become well mixed in the month or so during which it has been on its way.

Variability of the Current System

While it has been possible to make some estimate of the net movements, it must not be supposed that the system outlined above is very consistent from day to day. In the coastal streams from the Mull of Kintyre to Skye, the eastern shore of the North Minch, and the south shores of the Moray Firth and Firth of Forth, the driving force comes chiefly from the reduced density due to dilution. The movement of these streams and movements in estuarine regions are probably consistent in direction and approximately so in speed, though of course they will be responsive to large changes in rainfall. In the more open regions there is little doubt that variations are quite large and can include occasional reversal. For the east coast region the writer (Craig, 1957) has shown that the general southerly drift can vary between 2 and 17 kilometres per day (a mean figure of 5 kilometres per day is suggested above). To emphasise this, some further results are given in Fig. 14 showing returns of drift indicators in the summer of 1957. It will be clear that a period of relative quiescence was followed by an extremely rapid pulse.

The same sort of large variability probably applies in all the offshore areas, so that observations at times of special interest will be required until such time as the dependence of the water movements on wind (and any other important factors) is more precisely known.

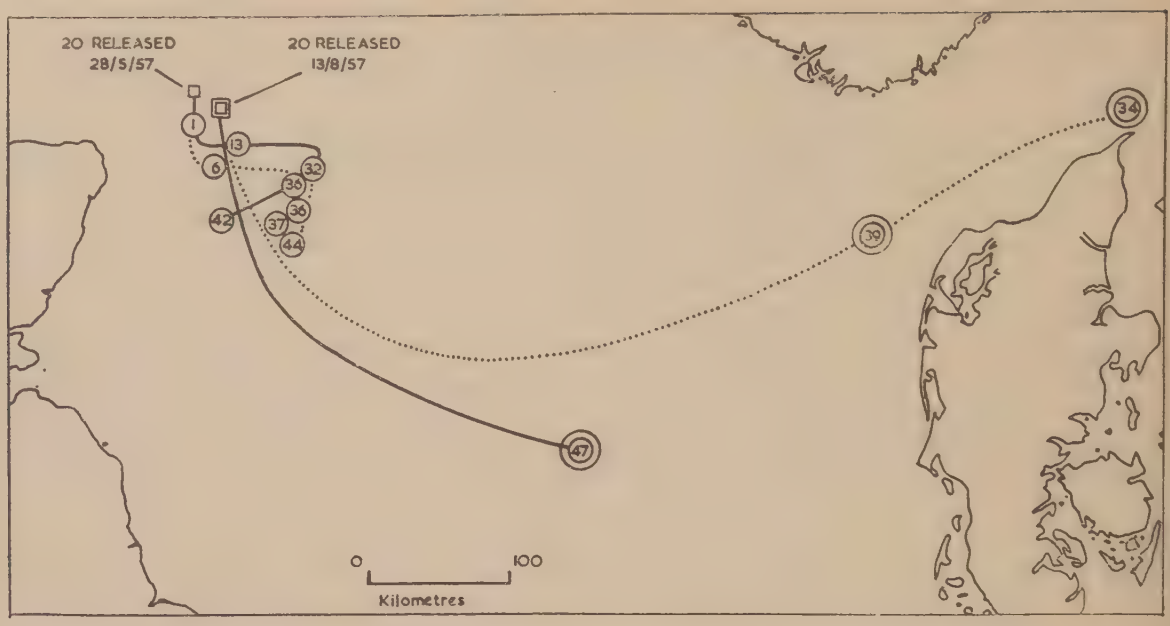

Fig. 14 An example of actual drift-indicator returns showing the variability of drift off the Scottish east coast. The first group of indicators gave a very good return and clearly show a slow and wavering drift southwards. By contrast the second group covered a great distance in a short time. The squares show the points of release, and circles the points of recovery. Single circles refer to the releases at the single squares, and double circles refer to releases at the double squares. Figures within the circles indicate the number of days adrift. The full lines trace the fortunes of indicators with a drogue at 75 metres depth, and the broken lines trace indicators with a drogue at 10 metres depth.

SECTION III.

SCOTTISH LOCHS AND INNER ESTUARIES

In order to emphasize the continuity of the coastal waters, various minor inlets of the coast have been considered, or neglected merely as sources of fresh water. Some of these inlets are of interest as illustrating hydrographic principles, and their importance as regards biology is much more than proportionate to the size of the areas concerned. For example in the case of the herring, these regions provide nursery grounds for many of the juvenile fish.

The West Coast Sea Lochs

These are in the main deep and surrounded by high hills. They may be divided roughly into two classes, those with a shallow sill at the entrance, which are the more numerous, and those without. In the cases where no sill exists we expect to find a simple vertical estuarine circulation, the deep water being at all times similar to that of the region outside, and the outflowing upper water being diluted. The degree of dilution and circulation must necessarily depend on the amount of fresh water entering the area.

Where a sill exists a thermocline is set up in the summer months at about sill depth. Below the thermocline, depletion of oxygen and accumulation of decomposition products goes on throughout the summer. It is not known whether any of the Scottish sea lochs ever become completely deoxygenated in their deep regions, but oxygen values of less than half those outside have been observed, and phosphate values six times greater.

It seems likely (Jennings, 1931) that width of the sill is important in determining how far the tendency to stagnation can proceed.

Examples of extreme conditions of this type mentioned above have been described by the writer (Jenkins, 1931). It should perhaps be mentioned that the lochs opening on to the Firth of Clyde are subject to the usual estuarine circulation, but because the Firth itself is a well-mixed system, the deep water of the lochs is in summer subject to the seasonal variations of the ocean proper.

The very complete account of the Clyde area by Hugh Robert Mill (1921) should be referred to for detail of the seasonal variations in the various parts of that region.

In the Clyde Estuary there are a number of sea lochs, characterized by greater width and less depth than those of the mainland. These have never been surveyed, but it is unlikely that they show the stagnation of stagnation, except in the case of Loch Long, and more general character almost entirely reflects that of the outside sea, with no more than moderate dilution, since the catchment areas of the Estuarine systems are necessarily small. Examples of these should be probably the only ones because of compromise characterizing these lochs from the outer estuary exist. The exchange rate of the water seems to be generally a matter of days, and it is therefore unlikely that the difference in water type results in significant differences in the phytoplankton. By contrast, some of the deep mainland sea lochs show great differences between productive within and without their entrances, of which a preliminary study has been made by Murray (1926).

The north west lochs, and the Orkney and Shetland ones are again practically unknown quantities so far as detail is concerned. They must, even more than the Hebridean lochs, be full of great variety, and in view of great variations in the hours the mainland ones may be filled with oceanic water. Tidal flow also is of a totally different order. It will be appreciated that these regions are present because which distinguish them rather sharply from the deep basin regions, and further survey is required before a description of the seasonal regime can be regarded as complete. Such work will contribute to our knowledge of the ecology of the common fauna whose distribution is dependent on the environment is now being closely studied.

The Cromarty, Inverness and Beauly Firths

These are relatively shallow, and characterised by very heavy dilution from the rivers. Each has an entrance of restricted width at which the depth increases locally to twenty or thirty fathoms. Far from having any similarity to the west coast lochs, these deep regions, being entrances rather than basins, are subject to violent scouring currents which almost certainly maintain their depth. For example, at the entrance to the Inverness Firth, tidal currents reach a velocity of about two knots. Superposed upon the to and fro tidal motion is the differential movement of upper and lower layers. By applying the formulæ of Appendix II, we can deduce that the usual rate of in- and outflow must be of the order of half a knot, i.e. the upper layer passes over the lower layer at a relative speed of about one knot. This rate of circulation is probably considerably exceeded in times of heavy flooding of the rivers. It is clear that the exchange time for water in the Inverness Firth is to be measured in hours rather than days.

The other firths are of similar though less extreme character, neither the Beauly nor the Conon being comparable to the Ness as a fresh water source.

The Firth of Tay

A description of this estuary is given by Alexander, Southgate and Bassindale (1935). From salinity data given by them we can deduce that the general form of the circulation, and its rate, is generally similar to that of the Inverness Firth, the maximum rate of circulation being in the reach from the Abertay Lightship to Broughty Ferry. However, it will be clear that in the vicinity of the lightvessel round the period of high water, the width of the outflow is not sharply restricted, and its velocity will be lower than in the case previously discussed.

The Upper Firth of Forth

The fresh water flow into this firth is considerably less than in either the Inverness Firth or the Firth of Tay. The region above Queensferry is both wider and deeper than these, and consequently this region is definitely more marine. At Grangemouth, however, the width and depth decrease considerably. Tidal

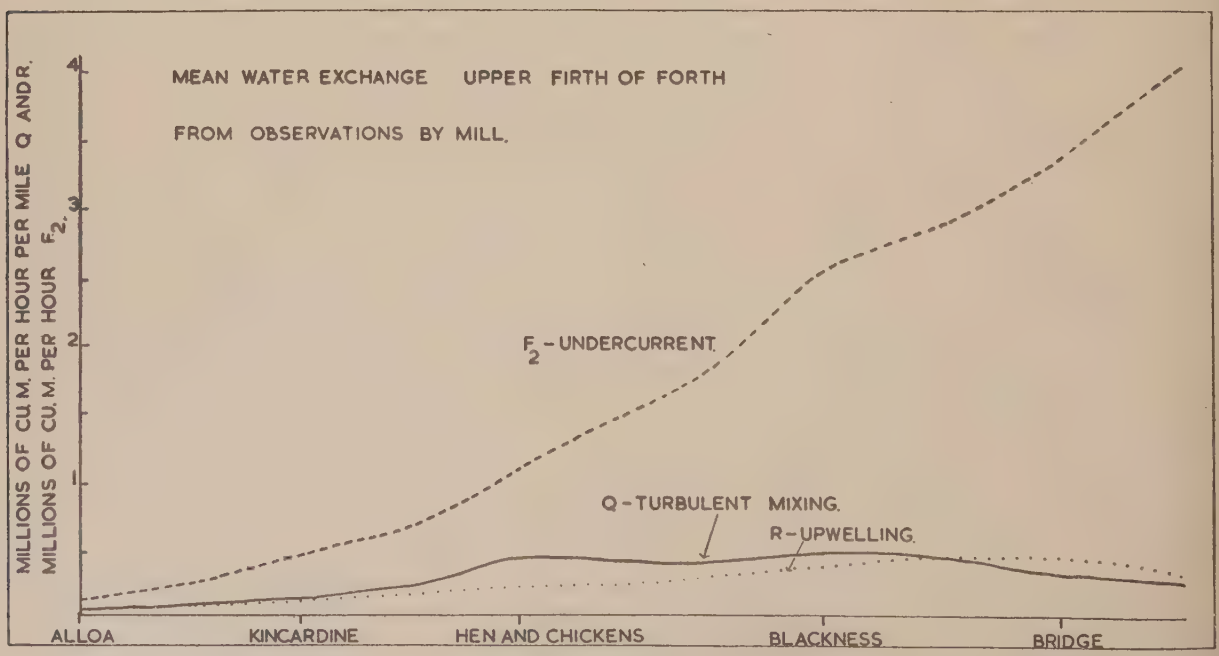

Fig. 15 Water exchanges in the upper Firth of Forth, using data from H. R. Mill (1885) and the methods of Appendix II.

rise and fall extend to about Stirling, but salt water does not extend so far as this, the ultimate limit at high water being about the mouth of the Devon, some 3 miles up river from Alloa.

The Firth of Forth, including this upper reach as far as Alloa, has been studied in some detail by Mill (1885) who gives mean salinities at surface and bottom at a series of stations. From these data, using the methods of Appendix II, the water exchange pattern for the upper region has been worked out, and mean values are given in Fig. 15.

The manner in which the various processes are distributed in the tidal cycle cannot be determined in this way, and so the figures must be regarded as showing the overall effects only, and applying to the mean tidal range. The mean fresh water discharge has been taken as 150,000 cubic metres per hour in making the calculations.

Two points of detail may help to fill in the picture. First, the *velocity* of the undercurrent naturally depends on its cross-section area as well as on the volume flow. The velocity is rather below half a knot in the section Hen and Chickens to Alloa. It is probable that it exceeds half a knot in times of flood, and drops to less than a quarter of a knot when the river is low. Secondly, the fact that turbulent mixing, Q, is greatest in the region from the Hen and Chickens to Blackness does not of course imply that the estuary is in the ordinary sense more turbulent in this region. The curve is an indication of turbulent mixing *per mile* of estuary. Naturally the intensity of mixing is to be measured in volume *per unit of area* and, by this standard, vertical mixing is about four times greater in the reach above Kincardine than in the wider part of the estuary lower down, having a value of about 13 centimetres per hour.

The velocity of the undercurrent also will be less in the wider and deeper part of the estuary, the high velocity in the Alloa-Kincardine reach dropping to values better expressed in miles per day. Near the Bridge, and upwards to Blackness, a value of three to four miles per day is perhaps a fair estimate.

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APPENDIX I

Conversion Table Salinity to D.C.I. (reprinted from Ann. Biol. Vol. X, p. 87).

S‰	D.C.I.	S‰	D.C.I.	S‰	D.C.I.
15·0	2·31	30·9	1·66	34·86	·81
15·5	2·30	31·0	1·65	34·88	·79
16·0	2·29	31·1	1·64	34·90	·78
16·5	2·28	31·2	1·63	34·91	·77
17·0	2·27	31·3	1·62	34·92	·76
17·5	2·26	31·4	1·61	34·93	·76
18·0	2·24	31·5	1·60	34·94	·75
18·5	2·23	31·6	1·59	34·95	·74
19·0	2·22	31·7	1·58	34·96	·74
19·5	2·21	31·8	1·57	34·97	·73
20·0	2·20	31·9	1·56	34·98	·72
20·5	2·18	32·0	1·54	34·99	·71
21·0	2·17	32·1	1·53	35·00	·70
21·5	2·15	32·2	1·52	35·01	·69
22·0	2·13	32·3	1·51	35·02	·68
22·5	2·12	32·4	1·50	35·03	·67
23·0	2·10	32·5	1·49	35·04	·66
23·5	2·08	32·6	1·47	35·05	·65
24·0	2·06	32·7	1·45	35·06	·64
24·5	2·04	32·8	1·44	35·07	·63
25·6	2·00	32·9	1·42	35·08	·62
25·8	1·99	33·0	1·40	35·09	·61
26·0	1·98	33·1	1·38	35·10	·60
26·2	1·97	33·2	1·36	35·11	·59
26·4	1·96	33·3	1·34	35·12	·58
26·6	1·95	33·4	1·32	35·13	·57
26·8	1·94	33·5	1·30	35·14	·56
27·0	1·93	33·6	1·28	35·15	·54
27·2	1·92	33·7	1·26	35·16	·53
27·4	1·91	33·8	1·23	35·17	·52
27·6	1·90	33·9	1·21	35·18	·51
27·8	1·89	34·0	1·18	35·19	·50
28·0	1·87	34·1	1·15	35·20	·49
28·2	1·86	34·2	1·12	35·21	·47
28·4	1·85	34·3	1·08	35·22	·45
28·6	1·84	34·4	1·04	35·23	·44
28·8	1·82	34·5	1·00	35·24	·42
29·0	1·81	34·50	1·00	35·25	·40
29·2	1·80	34·52	·99	35·26	·38
29·3	1·79	34·54	·98	35·27	·36
29·4	1·78	34·56	·97	35·28	·34
29·5	1·78	34·58	·96	35·29	·32
29·6	1·77	34·60	·95	35·30	·30
29·7	1·76	34·62	·94	35·31	·28
29·8	1·76	34·64	·93	35·32	·26
29·9	1·75	34·66	·92	35·33	·23
30·0	1·74	34·68	·91	35·34	·21
30·1	1·74	34·70	·90	35·35	·18
30·2	1·73	34·72	·89	35·36	·15
30·3	1·72	34·74	·88	35·37	·12
30·4	1·71	34·76	·87	35·38	·08
30·5	1·70	34·78	·86	35·39	·04
30·6	1·69	34·80	·85	35·40	·00
30·7	1·68	34·82	·83		
30·8	1·67	34·84	·82		

APPENDIX II

Notes on Estuarine Circulation

This treatment was developed particularly to deal with Scottish estuaries in which the only readily available information was the vertical distribution of salinity and the fresh water inflow. Some useful general considerations are given by Stommel (1953).

We suppose that we can measure the mean salinity of the inflowing and outflowing streams in the estuarine circulation. To do this we have to start with the mean vertical salinity distribution in a section or sections across the channel. For convenience we regard this as a vertical distribution at a 'station'. We start with observed salinities and consider what flow and mixing must occur to maintain these salinities.

Since the water in the brackish part of the estuary is being continually diluted by fresh water, it must, if conditions are to be steady, be re-salted by an upstream flow of greater salinity. In other words, to maintain steady conditions, other than fresh water conditions, there must be a division of the flow into a relatively fresh downstream current and a relatively salt upstream current.

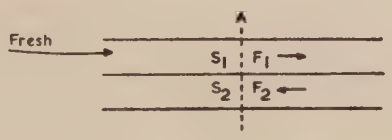

Fig. 16 Water exchange across a section, A, laid across a narrow estuary. See text.

A Single Station

Consider the conditions at a station, A, where the downstream flow is F_1 with a mean salinity of S_1, and the upstream flow is F_2 with a mean salinity S_2; F is the fresh water flow of the river (Fig. 16).

If conditions are to be steady, the total quanity (*a*) of water and (*b*) of salt in the estuary above A must be constant. So:—

$$(a)\ F_1 = F_2 + F$$

$$(b)\ F_1S_1 = F_2S_2$$

$$\text{so } (F_2 + F)S_1 = F_2S_2$$

$$\text{i.e. } F_2S_1 + F\,S_1 = F_2S_2$$

$$\text{or } F_2(S_2 - S_1) = F\,S_1$$

$$\text{i.e. } F_2 = F\left(\frac{S_1}{S_2 - S_1}\right) \text{ and } F_1 = F\left(\frac{S_2}{S_2 - S_1}\right)$$

$$\text{i.e. if we put } r = \frac{S_1}{S_2} \text{ then}$$

$$F_2 = F\left(\frac{r}{1 - r}\right) \text{ and } F_1 = F\left(\frac{1}{1 - r}\right)$$

e. the up and down flow can be deduced from the fresh water flow F, and the ratios of the down and up alinities.

Upstream Salinity Gradients

Consider a second station B situated a distance dx above the first. Let the corresponding salinities be $S_1 + dS_1$, $S_2 + dS_2$. Their ratio will be $r + dr$ and the currents $F_1 + dF_1$, $F_2 + dF_2$ respectively.

First of all we have

$$F_1 = F\left(\frac{1}{1 - r}\right)$$

$$\text{so } dF_1 = F\frac{1}{(1 - r)^2}\,dr \text{ which incidentally of course gives us}$$

$$dF_2 = F\frac{1}{(1 - r)^2}\,dr \text{ since } dF_1 = dF_2$$

$$\text{i.e. } \frac{dF_2}{dx} = F\frac{1}{(1 - r)^2}\frac{dr}{dx}$$

so for the upcurrent F_2 to decrease in intensity as we move upstream, $\frac{dr}{dx}$ must be negative, i.e. r must decrease as we move upstream. If the ratio $r = \frac{S_1}{S_2}$ were constant, the upstream current would be proceeding with undiminished intensity up the estuary.

Rate of Mixing Between the Streams

Consider the rates of salt transport at the station A, i.e. let $F_1S_1 = P_1$ and $F_2S_2 = P_2$.

In a distance dx as before we have

$$dP_2 = d(F_2S_2) = F_2dS_2 + S_2dF_2$$

The second term of this represents salt lost to the undercurrent by its *flow* vertically up through the boundary. The first term represents salt lost to the undercurrent on account of turbulent exchange of water between it and the upper current. Let this be equivalent to a circulation current Qdx through the boundary (Fig. 17).

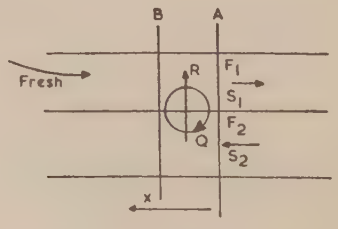

Fig. 17 Upwelling, R, and turbulent mixing, Q, in a short portion of a narrow estuary. See text.

Salt loss on account of Q is $Q(S_2 - S_1)dx$ which we equate to $F_2 dS_2$.

We obtain $Q = F_2 \dfrac{1}{(S_2 - S_1)} \dfrac{dS_2}{dx}$

$$\text{i.e. } Q = F \frac{S_1}{(S_2 - S_1)} \frac{1}{(S_2 - S_1)} \frac{dS_2}{dx} = F \frac{S_1}{(S_2 - S_1)^2} \frac{dS_2}{dx}$$

(Note: Q has the dimensions, e.g. galls., per yard per day.)

Summary of Basic Ideas

In any region we have if $r = S_1/S_2$

$$F_1 = F\left(\frac{S_2}{S_2 - S_1}\right) = F\left(\frac{1}{1 - r}\right)$$

$$F_2 = F\left(\frac{S_1}{S_2 - S_1}\right) = F\left(\frac{r}{1 - r}\right)$$

$$\frac{dF_1}{dx} = \frac{dF_2}{dx} = F \frac{1}{(1 - r)^2} \frac{dr}{dx} = R \text{ the upwelling per unit distance}$$

$$Q = F \frac{S_1}{(S_2 - S_1)^2} \frac{dS_2}{dx} = \frac{F}{S_1} \frac{r^2}{(1 - r)^2} \frac{dS_2}{dx}$$

$$\text{or } Q = \frac{F_2}{S_2 - S_1} \frac{dS_2}{dx} = \text{the rate of turbulent mixing per unit distance.}$$

Application of the Formulæ in Practice

(*a*) In simple estuaries where the breadth is of the order of $\frac{1}{4}$ mile or less we can neglect the effect of the earth's rotation. Provided the channel is of uniform depth, or the depth increases towards the sea, the preceding formulæ can be applied in a straightforward way. We are unable to calculate precisely the true mean of the salinity of the inflowing and outflowing streams, but estimates can be made from the vertical distribution of salinity which are likely to be good enough for practical purposes.

For example we may consider the types of vertical salinity distribution shown in Fig. 18: (*a*) is a situation with little vertical mixing; (*b*) rather more, and (*c*) considerable mixing. If these kinds of vertical distribution are typical of a considerable length of the channel, we should expect to find distributions of salinity of the general forms shown, which represent the isohalines in a section along the centre of the channel. Such distributions in their turn suggest velocity distributions as shown.

In justification for such estimates of velocity distribution, we note that they imply that the rate of flow at any depth is proportional to the degree of vertical stability at that depth. We note also that the depth of no motion must be taken such that the difference between out- and inflow is just equal to the fresh water flow, and that the net salt flow must be zero.

If these two conditions are not met, we must revise our estimate of the velocity distribution. However, in practice we seldom have sufficient detail for high accuracy and answers correct to about ± 30% are the most that can be expected. In the examples given, the estimates would be:

(*a*) $S_1 = 10‰$ $S_2 = 20‰$
(*b*) $S_1 = 11‰$ $S_2 = 19\frac{1}{2}‰$
(*c*) $S_1 = 12‰$ $S_2 = 19‰$

It will be seen that in the extreme situation (*c*) the crude approximation of taking S_1 and S_2, the surface and bottom values of salinity will lead to an underestimation of the undercurrent by only about 30%. Thus where only surface and bottom values are available, if we take them as our values of S_1 and S_2 and add 15% to the calculated values of the currents, we shall not be far in error.

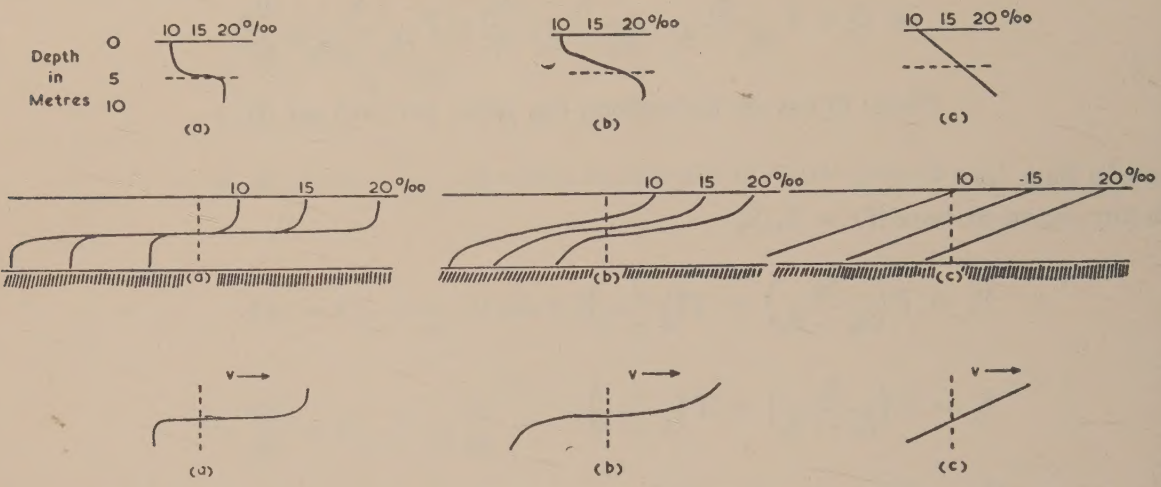

Fig. 18 Stratification of salinity and velocity in a narrow estuary. See discussion in text. The upper figures indicate salinity at a station. The centre figures show salinity in a section along the centre of the estuary. The lower figures show velocity distribution, the dotted vertical line corresponding to zero velocity. The case (*a*) is of an estuary with slight vertical mixing, (*b*) an intermediate case, and (*c*) considerable vertical mixing.

In general, and this applies also to larger scale effects, the more homogeneous are the inflowing and outflowing masses, the less need there is to have a precise picture of the distribution of velocity *within* each mass. In conclusion it should be added that where the channel is irregular, or decreases in depth towards the sea for part of its course, these ideas should be applied with caution, and other investigations made where possible. One would not, for example, try to treat a deep sea loch with a sill at the mouth, in this elementary fashion.

(*b*) When we consider the lower reaches of an estuary where the width becomes much greater than $\frac{1}{4}$ mile, the effect of the earth's rotation can no longer be ignored. In general, the outflowing upper layer will lie in a wedge against the right-hand shore, and the more saline water may be expected to occupy the remainder of the estuary and to have a net inward motion. It may indeed be subject to eddy motion, but the *average* motion *must* of necessity be inwards, and at a rate sufficient to replace the water which has become diluted and carried out by the ouflow.

To get an idea of the order of magnitude of the distances involved, we may suppose the wedge to be moving outwards at a rate of half a knot in relation to the main body. Then for a uniform temperature of 10°C. and a salinity difference of 10‰ between the wedge surface and the main body, the slope of the boundary surface AB will be about one metre per mile. For a salinity difference of 1‰, the slope will be about 10 metres per mile. Examples of the latter order of magnitude occur in the Firth of Forth, Moray Firth and the Minch. The former case of a 10‰ difference is not typical of any outer estuary in the Scottish region, but it will serve to show how it is that in the upper regions, of width below $\frac{1}{4}$ mile, we can legitimately neglect the slope of the boundary layer.

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